LLNL Final Design for PDV Measurements of Godiva for Validation of Multi-Physics Simulation

IER-268 CED-2 Report

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Auspices

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Disclaimer

Executive Summary

This document is a Final Design (CED-2) Report for IER-268, “PDV Measurements of Godiva for Validation of Multi-Physics Simulation”. These measurements will measure surface velocities in several locations, the initial α and α-t curve as a function of fission yield using existing LLNL assets including:

- The portable Photonic Doppler Velocimeter (PDV) detector,
- The “alpha box”, and
- Aluminum-encapsulated ^{235}U fission foils.

These experiments will be simulated using multi-physics methods funded separately under LLNL-AM2. A supercritical benchmark specification will be developed; and, if funding permits, an ICSBEP (or classified equivalent) evaluation will be published.

1.0 Introduction

Lawrence Livermore National Laboratory (LLNL) has an existing PDV instrument that *may* be capable of measuring surface velocities as a function of time at multiple locations on the Godiva-IV assembly. The PDV, together with the "alpha box" and ^{235}U foils developed for IER-147, will provide integral data for a supercritical Godiva-IV benchmark.

2.0 Budget and Scope of IER-268

LLNL has an authorized budget of $50,000 to support IER-268 measurements utilizing existing LLNL assets:

- LLNL Portable Photonic Doppler Velocimeter (PDV)
- LLNL "alpha box"
- LLNL aluminum-encapsulated ^{235}U foils

The budget will be utilized only for effort and travel expenses related to experiment introduction (CED-3a), experiment execution (CED-3b) and documentation of the experimental results (CED-4a). Collaboration with the NCNS Program, which has similar data needs, will allow cost savings by reducing duplicate measurements through shared data.

3.0 Preliminary Design (CED-1)

The LLNL PDV, "Alpha Box", and ^{235}U foils were identified previously in IER-176[1] as instruments able to determine surface velocity, alpha and the alpha-t curve, and yield, respectively. As the scope of IER-176 CED-1 subsumes IER-268 CED-1, this document focuses on final design.

4.0 Final Design (CED-2) Accomplishments

4.1 PDV. LLNL has a portable self-contained Photonic Doppler Velocimeter (PDV) detector system capable of high fidelity measurements of material velocity as a function of time, that can be integrated to give position versus time, at multiple surface locations simultaneously. The PDV was designed for experiments where materials are subjected to extreme conditions, such as subcritical experiments and hydro tests, and is believed to be well suited for fast burst reactor applications. LLNL has previously deployed the PDV at the Nevada National Security Site at both JASPER and DPF. Jose Sinibaldi and Tony Whitworth (B-Division) are the LLNL subject matter experts for the PDV detector. Ted Strand (retired) was the winner of a 2012 R&D 100 award as co-developer of this system (see Appendix B).

[1] LLNL-TR-521592, Godiva and Juliet Diagnostics CED-1 (IER-176), J. C. Scorby and W. Myers, December 23, 2011.

4.2 ^{235}U Foils. Aluminum-encapsulated ^{235}U foils were designed and fabricated by Dr. Roger Henderson, Chemical Sciences Division, LLNL, for IER-147[2] as an independent means of estimating the fission yield. The LLNL foil design contains a nominal 0.375-inch diameter uniform electrochemical deposit containing approximately 1 mg of ^{235}U encapsulated in aluminum. The outer dimensions of the encapsulation are 0.49-inch diameter (maximum) by 0.1-inch thickness (nominal). This foil is designed to fit in the LANL-designed foil holder[3] with internal diameter of 0.505-inches. At this time, LLNL has fabricated 80 foils. After irradiation by Godiva-IV, the ^{235}U foils will be transported to the LLNL NAD Lab in Mercury for neutron activation analysis (NAA). The essential isotopes to be measured are:

- Mo-99
- Zr-95
- Ce-144
- Nd-147

David Hickman (ES&H) and Bryan Bandong (Chemical Sciences Division) are the LLNL subject matter experts who will perform the NAA using a state-of-the-art Canberra portable Falcon 5000 HPGe detector with Genie 2000 gamma analysis software.

4.3 Alpha Box. Burst fission yields in Godiva IV have been measured and plotted against reciprocal reactor period or "alpha" showing excellent correlation of the form $Y = C\alpha(1+\alpha^2\tau^2)$, where C is a constant, α is the initial reciprocal reactor period, and τ is the inertial lag time equal to 8.9 μsec[4]. The inertial lag time may have changed since these earlier measurements in 1969 due to cracking of some of the fuel. The LLNL Test Readiness Program has offered to field their "alpha box" and analyze data to provide the time-dependent photon leakage from which the initial alpha and time-dependent (α,t) curve can be determined. This curve will also provide the burst width; i.e., the full-width at half-maximum value. Craig Halvorson and Mark May are the LLNL "alpha box" subject matter experts.

AWE is developing a Nuclear Forensics Detection System (NFDS) similar to the LLNL alpha box and has requested deployment of their system in parallel with the LLNL instrument. Neil McMillan is the AWE subject matter expert for their NFDS. This deployment is for testing purposes only as the AWE system is still in development. The system may not be ready for fielding.

Godiva operators use a gamma leakage measurement system based on a photomultiplier tube to measure the initial reactor period. The inverse of this value is the initial alpha and this value will be available for comparison. Additionally, full-width half-maximum burst-width is measured by the Godiva operators using a photodiode and temperature rise is

[2] LLNL-TR-635203, IER-147 CED-2 Report, LLNL Final Design for Determining Reference Values of the GODIVA-IV Radiation Field within the DAF, April 15, 2013.
[3] LANL Drawing No. 128Y271216, Assembly Sample Canister.
[4] T.F. Wimett, R.H. White, and R.G. Wagner, "Godiva IV," pp. 95-104, *Proceedings of the National Topical Meeting on Fast Burst Reactors*, Albuquerque, New Mexico, 1969.

measured by resistance temperature detectors (RTDs) in two core locations. Burst width[30,5] and temperature rise[6,7] can be correlated to the initial alpha and yield. The Godiva Crew Chief and Godiva operations subject matter expert is Joetta Goda (LANL).

5.0 Experiment Introduction (CED-3a)

Pending approval of CED-2, LLNL will proceed to experiment introduction, which includes:

- Development of shipping papers and AHJ inspections
- Development of a measurement plan
- Identification of all necessary elements of LANL work requests to enable introduction of LLNL equipment to the DAF, installation within NCERC, utilization by LLNL personnel and collaborators, handling of radioactive materials, return of equipment to LLNL

6.0 Godiva-IV Measurements (CED-3b)

A series of burst measurements in order of increasing yield at or near the values provided in Table 1 would be ideal. Due to collaboration with NCNS burst measurements, the number of bursts and their size will be selected by NCNS. Additional bursts for NCSP-only data collection may be necessary depending upon the NCNS schedule and data needs.

Table 1. Typical Godiva-IV Burst Data[6]

α	Yield	Burst Width	Temperature Increase
0.012×10^6 s^{-1}	7×10^{15} fissions	N/A	40 °C
0.033×10^6 s^{-1}	1×10^{16} fissions	105 μs	68 °C
0.056×10^6 s^{-1}	3×10^{16} fissions	55 μs	150 °C
0.090×10^6 s^{-1}	5×10^{16} fissions	32 μs	272 °C

Testing of the PDV fiber optic probes and electronics under the harsh radiation environment of Godiva IV will commence as early as possible to accommodate re-configuration if necessary and possible.

7.0 Publication (CED-4)

The experimental results of the CED-3b measurements will be published in a Laboratory report. LLNL-AM2 is an on-going task in the 5-Year Execution Plan to develop and

[5] WADD Technical Note 61-8, Part I, *Transient Radiation Effects on Electronics, Kukla Transient Radiation Tests*," Fig. 22, "Comparison of Kukla Burst Width Data with Analytical Expression for Pulse Width," January 1961.

[6] Burstsampler.xlsx, personal communication, David Hayes, LANL, November 1, 2012.

[7] WADD Technical Note 61-8, Part I, *Transient Radiation Effects on Electronics, Kukla Transient Radiation Tests*," Fig. 24, "Plot of α^{-1} Versus Temperature Rise ΔT," January 1961.

validate state-of-the-art multi-physics simulations and simulation of these measurements will be provided as part of this task. If funding permits, an ICSBEP (or classified equivalent) will be prepared.

8.0 Schedule Considerations

Godiva-IV is authorized to perform prompt burst operations to complete start-up (IER-194) and should be available to users in early FY2014. Since there are similar data needs for the NCSP and NCNS Programs, collaboration will save funds and a mutually acceptable schedule and work scope split will be agreed upon. Currently, measurements are scheduled for the week of April 14, 2014.

9.0 Project Risks and Risk Management

The PDV measurement *may* fail since sufficiently high radiation may degrade light transmission in the fiber optic cable. Therefore, this IER proposes to utilize the PDV for a range of pulse yields starting as low as possible and proceeding to greater yields.

The "alpha box" is shielded for electric and magnetic fields (EMF) but is sensitive to both neutrons and gammas. LLNL proposes to deploy this instrument "as is" without additional neutron shielding. If an initial alpha proves difficult to determine due to time-dispersion effects of the neutrons detected, then neutron shielding will be developed.

Appendix A

IER-268 CED-0 Report

REQUEST FOR INTEGRAL EXPERIMENTS FORM

Form Status: Final

Requestor Name:
Last Name: Heinrichs **First Name:** David **Middle Name:** Paul

Affiliation: Lawrence Livermore National Laboratory

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Telephone No.: 925/424-5679

Experiment Request Title: PDV Measurements

Description of Application/Purpose (same level of detail as in DOE-STD-3007-2007):
Existing LLNL PDV instrumentation may be capable of measuring surface velocity in multiple locations on the Godiva-IV critical assembly. The PDV, together with the LLNL "alpha box" and U-235 foils developed for IER-147, will provide integral data for a supercritical Godiva-IV benchmark. The PDV measurement may fail since it is not known whether high radiation levels may degrade fiber optic light transmission.

Type of Publication Method and Review:
ICSBEP International Technical Review Group evaluation and review publication method - or classified equivalent.

User Assessment of Available Integral Data (ICSBEP, Published, Unpublished, etc.):
No data currently available.

Suggested Experimental Concept (optional):
GODIVA-IV will be pulsed for a range of yields and (a) LLNL PDV will measure surface velocity; (b) LLNL alpha-box will measure the "alpha-t" curve; and (c) the U-235 foils will provide an independent measure of yield.

The Requestor acknowledges all information is approved for public release. ☑ I Agree

DC Name or Review and Release Number: John C. Scorby

Appendix B

Ten Times More Data for Shock-Physics Experiments

FOR years, scientists conducting shock-physics experiments were limited to measuring sudden velocity increases at only a few discrete points on a target's surface. For example, as recently as a year ago, the high costs and complexity of setup forced researchers at the National Nuclear Security Administration (NNSA) laboratories to collect velocity data at only a dozen or so points on a moving surface as part of stockpile stewardship experiments. These scientists then used extrapolation, assumptions, and models to determine what was occurring in regions of the experimental target not observed directly.

Today, scientists are routinely recording 96 channels of optical velocity data at a fraction of the former cost to acquire data from just a few channels. This new technology, for which its developers earned an R&D 100 Award, is called multiplexed photonic Doppler velocimetry (MPDV).

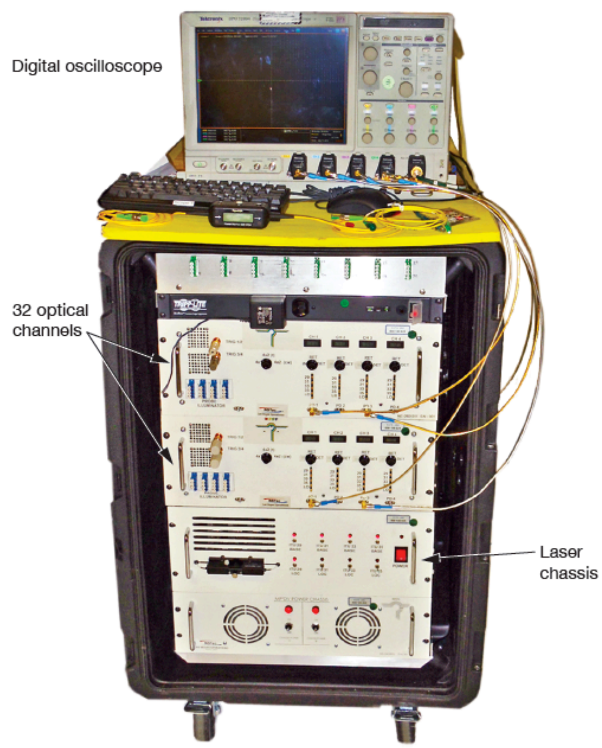
The MPDV system was designed and developed by a team from NNSA's National Security Technologies (NSTec), LLC, the managing and operating contractor for the Nevada National Security Site and its related facilities, including operations in Los Alamos and Nevada. Senior scientist Ed Daykin led the development team together with Livermore physicist Ted Strand. The project began under NSTec's Site Directed Research and Development Program, and final development was conducted under the Shock Wave Related Diagnostic Development Project, which addresses the diagnostic needs of the NNSA nuclear design laboratories (Lawrence Livermore, Los Alamos, and Sandia national laboratories) in the area of shock physics.

Beat Frequency a Matter of Subtraction

MPDV is an optical velocimeter, a group of noncontact diagnostics that measure the velocities of explosively driven metal surfaces in single-shot shock-physics experiments. These surfaces may be driven to kilometer-per-second velocities in less than a billionth of a second. MPDV is a significant improvement over photonic Doppler velocimetry (PDV), which was pioneered by Strand. He searched in the early 2000s for an optical-based technique that was easier to deploy and more cost-effective than two other instruments: the Fabry–Perot velocimeter, developed at Livermore, and the commercially available VISAR (velocity interferometer system for any reflector).

PDV is based on determining the "beat frequency," the difference in frequency between two waves, in this case, the difference in frequencies between a reference laser and the Doppler-shifted light reflected from a moving surface. Over the years, PDV became a standard diagnostic tool available to Livermore researchers. (See *S&TR,* July/August 2004, pp. 23–25.)

Strand explains that although highly reliable, PDV cannot economically provide the many dozens of simultaneous



A compact multiplexed photonic Doppler velocimetry (MPDV) system includes a 20-gigahertz digital oscilloscope for recording data, 32 optical channels for simultaneously measuring 32 discrete surface velocities, and a chassis for powering the lasers that are used to determine the beat frequency—a combination of the Doppler-shifted light from one laser and the reference light from another laser.

measurements needed to improve physical understanding and experimental accuracy in some stockpile stewardship experiments. In particular, Los Alamos and Lawrence Livermore scientists performing hydrodynamics experiments requested a more portable and cost-effective diagnostic system that could record more than 100 points of optical velocimetry data. Hydrodynamics experiments monitor the movement of a curved imploding surface inside a domelike configuration. In these experiments, the detonation of high explosives sends a shock wave through the test material, causing a liquidlike flow. Liquid behavior is described by hydrodynamic equations, so the experiments are often called hydrotests. (See the related article beginning on p. 16.)

Livermore MPDV codeveloper Ted Strand.

More Information at Reduced Cost

In response to the experimenters' requests, the MPDV development team increased the data-recording capacity of PDV by nearly an order of magnitude and reduced the cost per data channel fivefold. Built entirely from commercially available components, MPDV incorporates frequency- and time-division multiplexing to provide increased channel count, simultaneously measuring up to 32 discrete surface velocities onto a single digitizer. Frequency-division multiplexing sends signals in several distinct frequency ranges at a given time. Time-division multiplexing involves sequencing groups of data from individual input streams, one after the other, in such a way that they can be associated with the appropriate receiver. The equipment is designed to be set up and operated by one person per 32-channel system. While traditional PDV cannot discern between forward- and backward-traveling surface motion, MPDV measures the direction of travel.

MPDV uses a fiber-optic interferometer that measures the beat frequency resulting from a combination of the Doppler-shifted light from one laser and the reference light from another laser—an approach referred to as the heterodyne method. The Doppler-shifted light from four different probes is combined with four different reference light frequencies and applied to a photodetector. This process is accomplished within a fiber-coupled system that leverages commercially available telecommunications hardware. The beat frequency is recorded onto a high-bandwidth (20-gigahertz) digitizing oscilloscope and is then analyzed to determine velocity versus time at any of the surface locations that were monitored.

With MPDV, scientists can make hundreds of velocity measurements between 0.001 to 30 kilometers per second that are both economical and logistically feasible. The portable MPDV system requires no special laser safety requirements.

Proof-of-concept experiments were conducted in early 2011. The technology was first demonstrated at Los Alamos in August and September of that year. MPDV was then fielded on two multimillion-dollar experiments in October and December at Lawrence Livermore and Los Alamos, respectively. On March 7, 2012, a record 96 channels were demonstrated using three MPDV units.

By providing scientists with much more high-quality data, MPDV improves the ability to predict shock and material conditions and allows detailed comparisons between computational and experimental results. In this way, the technology helps ensure the safety and security of the nation's nuclear stockpile.

The new capability has potential applications to pulsed-power experiments as well as low-velocity commercial applications such as noncontact measurements of vibration. The team plans to continue development with an eye on increasing channel count, improving cost-effectiveness, and enhancing measurement capabilities.

—Arnie Heller

Key Words: fiber-optic interferometer, hydrodynamics test, multiplexed photonic Doppler velocimetry (MPDV), R&D 100 Award, shock physics.

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